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TITLE: DYNAMICAL CALCULATION OF THRESHOLDS FOR COMPOUND-NUCLEUS FORMATION

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DYNAMICAL CALCULATION OF THRESHOLDS FOR COMPOUND-NUCLEUS FORMATION

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INTRODUCTION

A necessary condition for forming a compound nucleus in a heavy-ion reaction is that the dynamical trajectory of the fusing system pass inside the fission saddle point in a multidimensional deformation space. For nuclear systems lighter than a critical size and for relatively low angular momentum, the fission saddle point lies outside the point of hard contact, and this requirement is automatically satisfied once a one-dimensional interaction barrier is overcome. However, for heavier nuclear systems and/or for high angular momentum, the fission saddle point lies inside the contact point, and the center-of-mass bombarding energy must then exceed the maximum in the one-dimensional interaction barrier by an amount ΔE in order to form a compound nucleus. This was recognized[1,2] already in 1969, and since 1973 dynamical trajectories for fusing systems have been calculated by use of several approaches.[3-17]

In one approach,[3-7] classical equations of motion were solved numerically for a system whose shape is specified in terms of smoothly joined portions of three quadratic surfaces of revolution, with realistic expressions for the energies and forces involved. For symmetric systems, which have been considered most extensively within this approach, three collective coordinates are required. Although some calculations included two body viscosity,[18,19]

most were performed for zero dissipation.

In another approach, pioneered by Swiatecki,[8-11] classical equations of motion were solved approximately in closed form for a system whose shape is specified in terms of two spheres connected by a conical neck, with schematic expressions for the energies and forces involved. Nuclear dissipation was calculated by expanding the one-body wall-and-window formula[19-21] to third order in the neck radius. The solution of this schematic model is characterized by five constants, some of whose values have been estimated both theoretically[8,12-14] and from comparisons[9-11] with experimental data.[22] The theoretical estimates have been made by use of both the original schematic model[8] and improved models,[12-14] in which the nuclear shape is specified in terms of two spheres connected smoothly by a hyperboloidal neck, the collective potential and kinetic energies and one-body wall-and-window dissipation are calculated more accurately, and the equations of motion are integrated numerically.

In still another approach,[15-17] the time-dependent Hartree-Fock equations of motion were integrated numerically for a two-dimensional grid corresponding to axially symmetric nuclear shapes. For moderately heavy systems, the onset of fusion is at an energy considerably above the maximum in the interaction barrier, and this phenomenon is at least qualitatively related to the energy thresholds found in the macroscopic studies.[3-14]

All of the theoretical approaches discussed above predict that for sufficiently heavy nuclear systems and/or high angular momentum the center-of-mass bombarding energy must exceed the maximum in the one-dimensional interaction barrier by an amount ΔE in order to form a compound nucleus. The necessity for such an additional energy has been suggested experimentally in several recent studies,[9-11,22-27] although an alternate interpretation in terms of large surface friction has been proposed.[28] (The opposite conclusion

obtained in an earlier study[29] was based on comparisons with a schematic model,[8] whose estimated constants are now known to be unreliable.) Although the comparisons with experimental data have sometimes been interpreted as evidence for one-body wall-and-window dissipation, it must be borne in mind that the additional energy arises from the need to overcome both repulsive Coulomb and/or centrifugal forces on the one hand and dissipative forces on the other hand. In the comparisons made to date, no attempt has been made to distinguish between conservative and dissipative forces.

It is our major purpose here to calculate within a single unified model the dependence of the additional energy ΔE upon Z^2/A for various types of dissipation, in an effort to ultimately determine the magnitude and mechanism of nuclear dissipation from comparisons with experimental data. Since both our predictions and those of other groups depend somewhat upon the details of the model, we also study the effect of the shape parametrization on the dynamical thresholds.

DYNAMICAL MODEL

We focus from the outset on a few collective degrees of freedom that are most important and describe the nuclear shape by means of the three-quadratic-surface parametrization,[30] in which an axially symmetric shape consists of smoothly joined portions of three quadratic surfaces of revolution. For this paper we consider only head-on mass-symmetric collisions, which reduces the number of independent collective coordinates to three. It is convenient to project out of this three-dimensional space two moments of the distribution that have special physical significance. These are defined by[3-7,18,19]

$$r = 2 \langle z \rangle \qquad (1)$$

and

$$\sigma = 2 \langle (z - \langle z \rangle)^2 \rangle^{1/2} , \tag{2}$$

where z is measured along the symmetry axis and the angular brackets denote an average over the half volume to the right of the midplane of the reflection-symmetric shape. The moment r gives the distance between the mass centers of the two colliding ions, while σ measures the fragment elongation or the necking in the combined system. In general, they are functions of the N collective coordinates $q = q_1, \ldots, q_N$ that specify the shape of the system.

The nuclear potential energy of deformation V(q) is calculated in terms of a Coulomb energy and a double volume integral of a Yukawa-plus-exponential folding function,[31] with values of the constants determined in Ref. 32. The collective kinetic energy is given by

$$T = \frac{1}{2} M_{ij}(q) \dot{q}_i \dot{q}_j - \frac{1}{2} [M(q)^{-1}]_{ij} p_i p_j , \tag{3}$$

where the collective momenta p are related to the collective velocities $\dot{q}$ by

$$p_i = M_{ij}(q) \dot{q}_j . \tag{4}$$

Throughout this paper we use the convention that repeated indices are to be summed over from 1 to N. The inertia tensor M(q), which is a function of the shape of the system, is calculated for incompressible, nearly irrotational flow by use of the Werner-Wheeler approximation.[18,30]

The coupling between the collective and internal degrees of freedom gives rise to a dissipative force, whose average component in the ith direction may be written as

$$F_i = - \eta_{ij}(q) \dot{q}_j = - \eta_{ij}(q) [M(q)^{-1}]_{jk} p_k . \tag{5}$$

For the calculation of the shape-dependent dissipation tensor η that describes the conversion of collective energy into internal single-particle excitation energy, we consider zero dissipation, ordinary two-body viscosity,[18,19] one-body wall-formula dissipation,[19-21] and one-body wall-and-window dissipation.[19-21] For ordinary two-body viscosity, we use the viscosity coefficient $\mu = 0.02$ TP, which optimally reproduces average fission-fragment kinetic energies for the fission of nuclei at high excitation energies throughout the Periodic Table when the most recent constants[32] of the Yukawa-plus-exponential potential are used. The two types of one-body dissipation differ from each other in the following way: In the wall formula all velocities normal to the nuclear surface are measured relative to the stationary center of mass of the combined system and no window term is included, whereas in the wall-and-window formula surface normal velocities for a given half of the system are measured relatiave to the moving center of mass of that half, and an additional term is included to describe dissipation arising from the flux of particles through the window separating the two halves.

During the approach of the two nuclei from infinity and until a substantial neck has developed, we constrain the nuclei to spheres. After contact the nuclear density is assumed to remain constant throughout the shape, with the displaced matter forming a hyperboloidal neck. For all cases except zero dissipation, we calculate the dissipative force during the approach and contact stages from Randrup's proximity window dissipation model,[33] which takes into account the momentum transfer between the two nuclei when single particles pass through the window. When the neck radius reaches a critical size, which is taken to be 3.0 fm for all cases except wall-and-window dissipation, where it is taken to be 3.5 fm for numerical reasons, we switch to the full three-quadratic-surface parametrization.

The trajectory for the average dynamical path is determined by solving numerically the generalized Hamilton equations[18]

$$\dot{q}_i = (M^{-1})_{ij}\, p_j \tag{6}$$

and

$$\dot{p}_i = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial (M^{-1})_{jk}}{\partial q_i}\, p_j\, p_k - \eta_{ij}\,(M^{-1})_{jk}\, p_k \,. \tag{7}$$

CALCULATED RESULTS

In our studies of the dynamics of heavy-ion reactions, we are especially concerned with whether a particular collision leads to compound-nucleus formation. For this purpose, we plot in r-σ deformation space both the dynamical trajectory for a particular reaction and the location of the saddle point for the combined system. The criterion[6] adopted for compound-nucleus formation is that the trajectory in r-σ space pass inside (to the left of) the saddle point. When the trajectory passes outside (to the right of) the saddle point, the system reseparates in a fast-fission[34] or deep-inelastic reaction.

We also obtain the threshold energy for compound-nucleus formation. This minimum energy required to produce a compound nucleus is determined by finding the dynamical trajectory that just passes through the saddle point. Since our calculations are for mass-symmetric reactions, there is no difference here between the true saddle point and the conditional saddle point for fixed mass asymmetry.[8-14] Thus, the fusion that we obtain is exclusively compound-nucleus formation, with no contribution from mass-equilibrated fast fission.[34]

For the reaction $^{110}Pd + {}^{110}Pd \rightarrow {}^{220}U$ at a center-of-mass bombarding energy that exceeds the maximum in the one-dimensional interaction barrier by

20 MeV, we show in Fig. 1 dynamical trajectories for five different types of dissipation. In addition to the four types previously mentioned, we include an example of pure window dissipation, obtained by omitting the wall contribution in wall-and-window dissipation. The dynamical paths for no dissipation and two-body viscosity, which are very similar because the viscosity coefficient $\mu = 0.02$ TP is relatively small, prefer changes in separation r rather than neck formation σ and lead to compound-nucleus formation. On the other hand, the one-body-dissipation models all generate trajectories in which σ changes much more rapidly than r, leading to reseparation rather than compound-nucleus formation.

For this same reaction and bombarding energy, we show in Fig. 2 dynamical trajectories for four types of dissipation when the end bodies are constrained to be spherical, which is a widely used approximation.[12-14] The most dramatic effect on the trajectories occurs for two-body viscosity, where the spherical constraint leads to more compressed shapes in Fig. 2 compared to the unconstrained shapes in Fig. 1. As shown in Table 1, constraining the ends to be spherical can lead to significant differences in the calculated additional energy ΔE required to form a compound nucleus. For example, for the wall formula the additional energy ΔE is about 30 MeV larger when the spherical constraint is not imposed.

For each of the four types of dissipation considered, we have calculated the additional energy ΔE required to form a compound nucleus as a function of Z^2/A for the combined system, with the requirement that the target and projectile each lie along Green's approximation to the valley of β-stability.[35] As shown in Fig. 3, for both types of one-body dissipation, which correspond to highly overdamped motion, our calculated values of ΔE are in general an order of magnitude larger than those for zero dissipation and ordinary two-

body viscosity, which correspond to underdamped motion. The values of ΔE for wall-formula dissipation are larger than those for wall-and-window dissipation primarily because the surface normal velocities measured relative to the stationary center of mass of the entire system in the former case are larger than the normal velocities measured relative to the moving centers of mass of each half of the system in the latter case.

Above the threshold value $(Z^2/A)_{thr}$ which depends somewhat upon dissipation, our calculated dependence of ΔE on $Z^2/A - (Z^2/A)_{thr}$ contains a linear component because we begin our dynamical calculation in the three-quadratic-surface parametrization for a shape with a nonzero neck radius. To lowest order, ΔE depends quadratically[8-11] on $Z^2/A - (Z^2/A)_{thr}$ when the initial conditions correspond to starting with spheres at the top of the one-dimensional interaction barrier moving radially inward with kinetic energy ΔE. However, this lowest-order quadratic dependence is destroyed when dynamical effects that occur during the approach and contact stages are taken into account. Also, quantal sub-barrier tunneling destroys the quadratic dependence. Therefore, little physical significance should be attached to the lowest-order functional dependence of ΔE on $Z^2/A - (Z^2/A)_{thr}$ and consequently to the precise value of $(Z^2/A)_{thr}$. Instead, attention should be focused on the rate of increase of ΔE with increasing Z^2/A a few MeV above the threshold.

COMPARISON WITH EXPERIMENTAL DATA

In order to compare our results calculated for symmetric systems with experimental values, it is necessary to scale the asymmetric systems that have been studied experimentally into symmetric ones. Near the contact region, the effective value[8-14,22-27,29]

$$(Z^2/A)_{eff} = 4\ Z_1\ Z_2/[A_1^{1/3}\ A_2^{1/3}(A_1^{1/3} + A_2^{1/3})] \qquad (8)$$

defined in terms of the atomic numbers and mass numbers of the projectile and target provides an approximate scaling. Because the dynamical trajectory of a fusing system moves from the contact region, where $(Z^2/A)_{eff}$ is appropriate, to the saddle-point region, where Z^2/A for the combined system is appropriate, scaling in terms of the geometric mean[11,12,23]

$$(Z^2/A)_{mean} = [(Z^2/A)(Z^2/A)_{eff}]^{1/2} \qquad (9)$$

should be approximately valid. This expectation can be verified by replotting the results presented in Fig. 4 of Ref. 13 versus $(Z^2/A)_{mean}$ instead of $(Z^2/A)_{eff}$, which largely reconciles Feldmeier's calculations for asymmetric systems with those for symmetric systems presented in Table 1 of Ref. 13. The more recent calculations for asymmetric systems by Błocki and Swiatecki[12] also support the choice of $(Z^2/A)_{mean}$ for a scaling variable.

Figure 4 compares our calculated values of the additional center-of-mass bombarding energy ΔE required for compound-nucleus formation with existing experimental values. Solid symbols denote values extracted from measurements of evaporation residues,[23,24,29] which require the formation of true compound nuclei. Open symbols denote values extracted from measurements of nearly symmetric fission-like-fragments,[9,25,26] where fast-fission processes contribute in addition to true compound-nucleus formation. For both the solid and open symbols, the experimental values of the additional energy ΔE are determined by subtracting from the experimental barrier heights extrapolated values that correctly reproduce the smooth trends for somewhat lighter nuclei. For consistency with recent practice,[9-11,23] these extrapolated values are taken to be 96% of the barrier heights calculated[23] with the proximity po-

tential[36] for all cases except the open triangle, where the procedure of Ref. 26 is followed.

Taken together, all experimental values of ΔE in Fig. 4 agree much better with results calculated for underdamped motion arising from two-body viscosity than with results calculated for overdamped motion arising from either type of one-body dissipation. However, because the solid symbols usually lie somewhat above the open symbols, and because the error bars for the three solid symbols with the largest values of $(Z^2/A)_{mean}$ extend to ∞, this conclusion must be regarded as tentative.

OUTLOOK

We are on the brink of determining the magnitude and mechanism of nuclear dissipation. To do this unambiguously, we need further evaporation-residue measurements, which represent the only definitive proof of compound-nucleus formation, for heavy nearly symmetric systems spanning the threshold region. As an alternative approach, calculations are presently underway for some asymmetric systems that have been studied experimentally.

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Table 1. Calculated additional energy ΔE relative to the maximum in the one-dimensional interaction barrier required to form a compound nucleus in a head-on collision for $^{110}Pd + {}^{110}Pd \rightarrow {}^{220}U$. The neck radius r_n at which the three-quadratic-surface numerical integration begins is 3.0 fm unless indicated otherwise.

Type of dissipation	ΔE (MeV)	
	Full three-quadratic-surface parametrization	Spherical ends
No dissipation	1.5 ± 0.2	4.5 ± 0.1
Two-body viscosity, μ = 0.02 TP	5 ± 0.5	0.5 ± 0.5
Wall formula	90 ± 2	60 ± 2
Wall and window	———	36 ± 0.5
Wall and window, r_n = 3.5 fm	39 ± 0.5	32 ± 0.5

FIGURE CAPTIONS

Fig. 1. Effect of dissipation on dynamical trajectories in the r-σ plane for the reaction $^{110}Pd + {}^{110}Pd \rightarrow {}^{220}U$ at $\Delta E = 20$ MeV in the full three-quadratic-surface parametrization. The interval ΔE is defined as the difference between the bombarding energy in the center-of-mass system and the maximum in the one-dimensional interaction barrier. The moment r is the distance between the centers of mass of the two halves of the system, and the moment σ is the sum of the root-mean-square extensions along the symmetry axis of the mass of each half about its center of mass, both measured in units of the radius R_0 of the combined system. Solid circles indicate the single-sphere and tangent-spheres configurations, and the open circle indicates where the neck radius is 3.0 fm. At this point the three-quadratic-surface numerical integration begins for all cases except wall-and-window dissipation, for which it begins when the neck radius is 3.5 fm. The saddle-point configuration for the combined system is indicated by a cross (×).

Fig. 2. Effect of dissipation on dynamical trajectories in the r-σ plane for the reaction $^{110}Pd + {}^{110}Pd \rightarrow {}^{220}U$ at $\Delta E = 20$ MeV when the end bodies are constrained to be spherical. (In this figure the three-quadratic-surface numerical integration begins when the neck radius is 3.0 fm also for wall-and-window dissipation.)

Fig. 3. Effect of dissipation on the additional center-of-mass bombarding energy ΔE relative to the maximum in the one-dimensional interaction barrier required to form a compound nucleus in a head-on collision. The smooth curves are drawn by hand through the calculated points. The value of Z^2/A refers to the combined system, with the symmetric target and projectile chosen to lie along Green's approximation to the valley of β-stability (Ref. 35).

Fig. 4. Comparison of additional energy ΔE required for compound-nucleus formation calculated for symmetric systems with experimental values for asymmetric systems characterized by $(Z^2/A)_{mean}$, defined by Eq. (9). Values extracted from evaporation-residue measurements are represented by solid symbols (●, Ref. 24; ■, Ref. 29; and ▲, Ref. 23), whereas values extracted from measurements of nearly symmetric fission-like fragments are represented by open symbols (○, Ref. 9; □, Ref. 25; and △, Ref. 26).

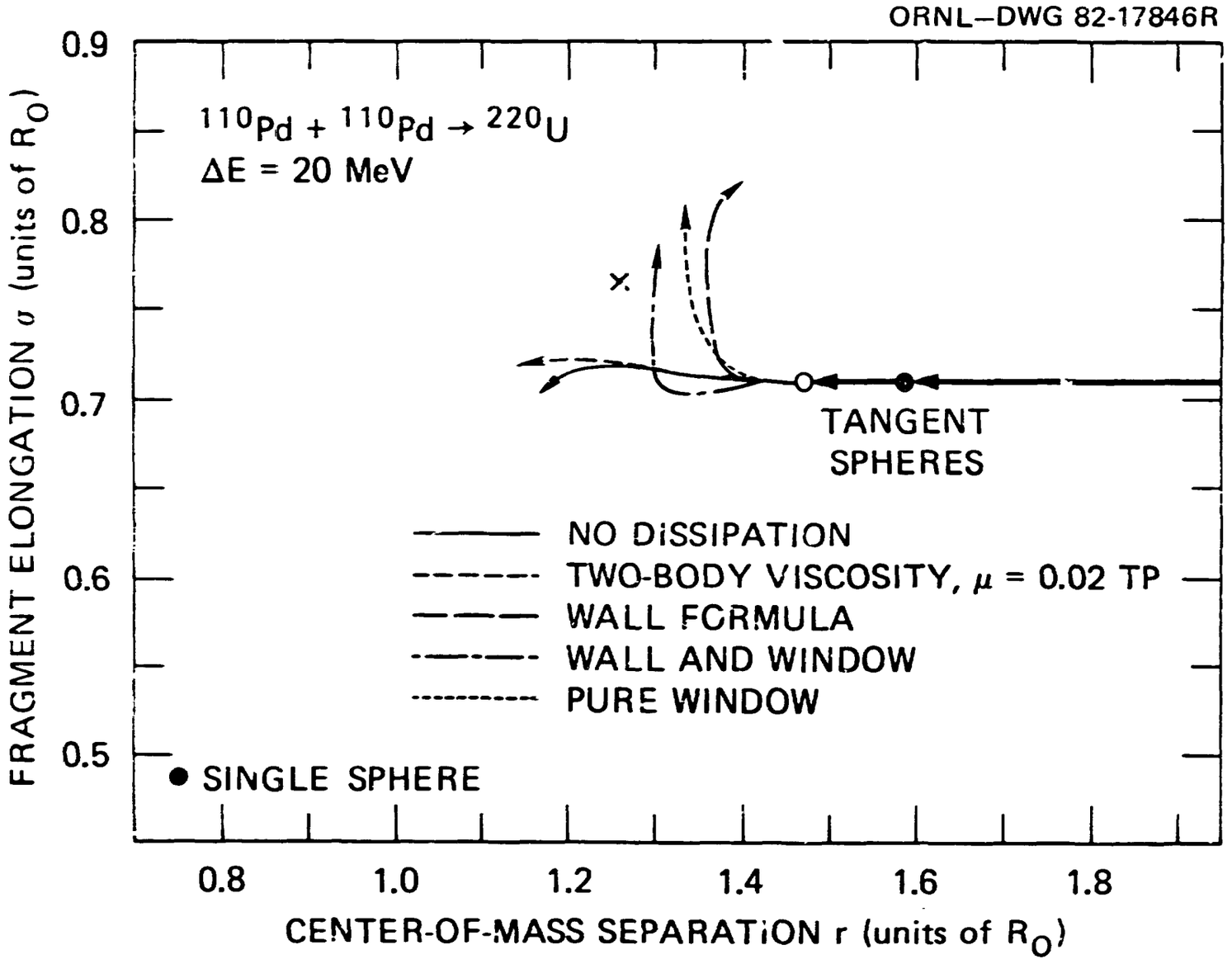
ORNL–DWG 82-17846R
$^{110}Pd + {}^{110}Pd \rightarrow {}^{220}U$
ΔE = 20 MeV
TANGENT SPHERES
NO DISSIPATION
TWO-BODY VISCOSITY, μ = 0.02 TP
WALL FORMULA
WALL AND WINDOW
PURE WINDOW
SINGLE SPHERE
FRAGMENT ELONGATION σ (units of R_O)
CENTER-OF-MASS SEPARATION r (units of R_O)
0.9
0.8
0.7
0.6
0.5
0.8
1.0
1.2
1.4
1.6
1.8

Figure 1.

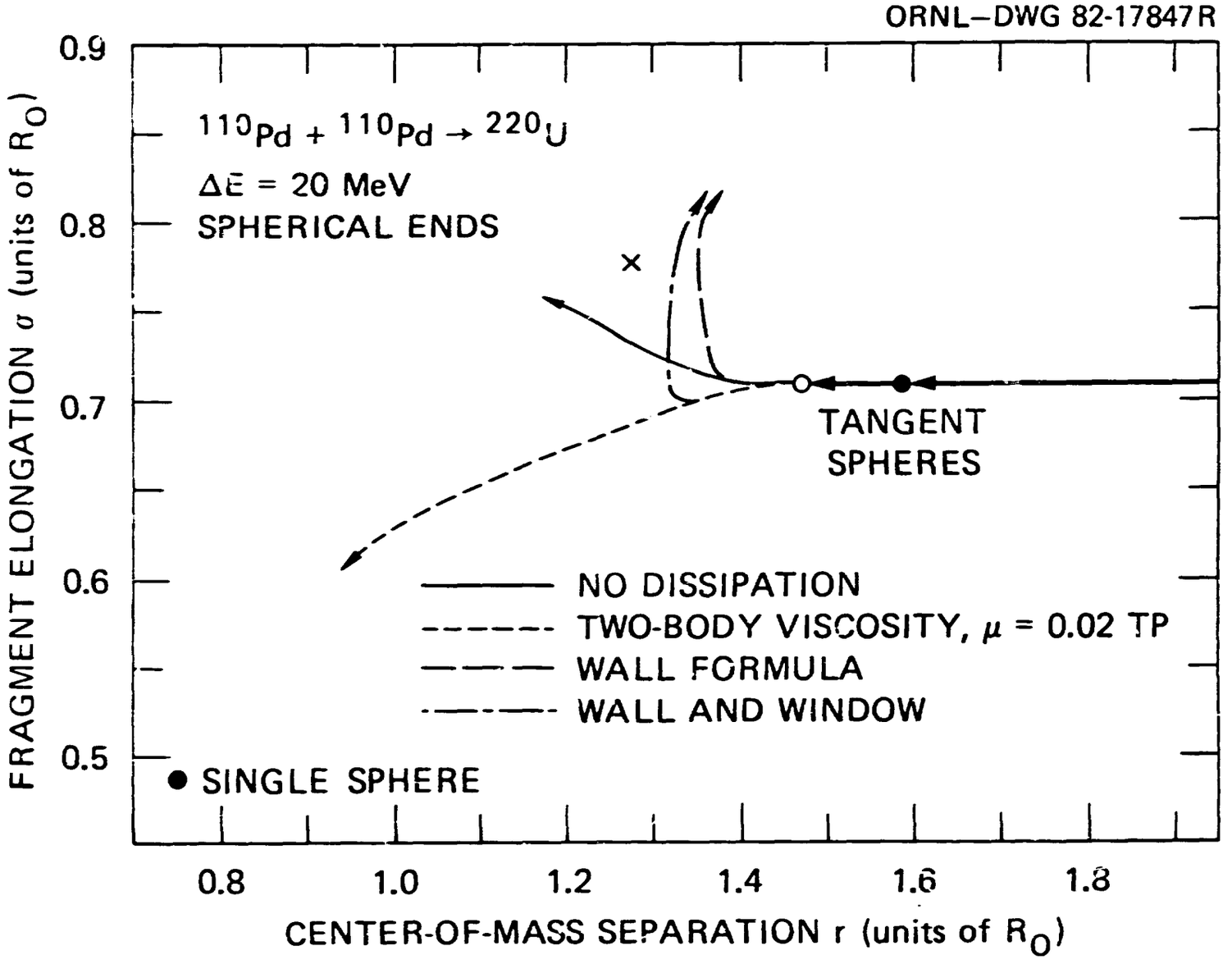
ORNL–DWG 82-17847R
$^{110}Pd + {}^{110}Pd \rightarrow {}^{220}U$
ΔE = 20 MeV
SPHERICAL ENDS
TANGENT SPHERES
NO DISSIPATION
TWO-BODY VISCOSITY, μ = 0.02 TP
WALL FORMULA
WALL AND WINDOW
SINGLE SPHERE
FRAGMENT ELONGATION σ (units of R_0)
CENTER-OF-MASS SEPARATION r (units of R_0)
0.9
0.8
0.7
0.6
0.5
0.8
1.0
1.2
1.4
1.6
1.8

Figure 2.

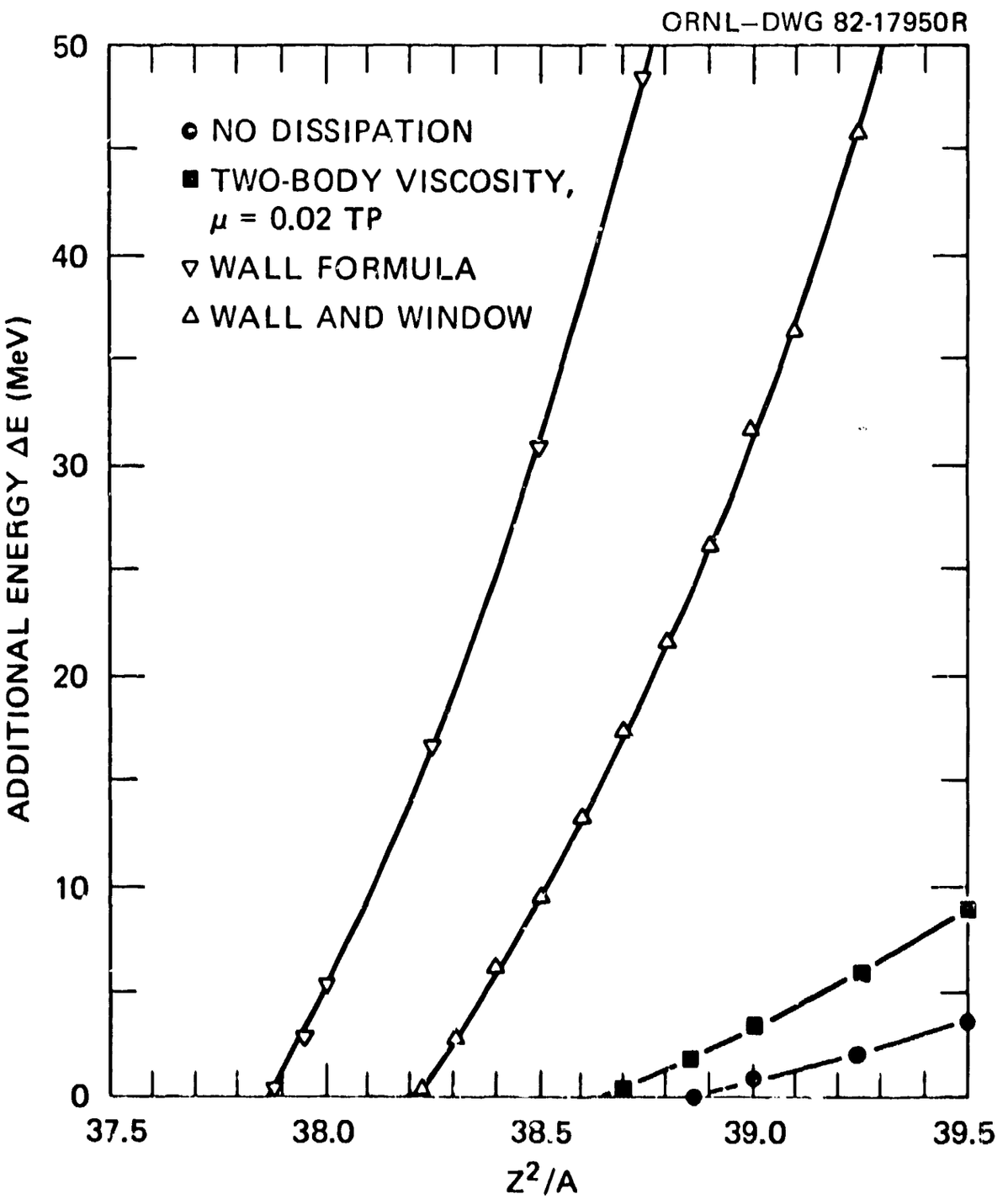
ORNL–DWG 82-17950R
NO DISSIPATION
TWO-BODY VISCOSITY, μ = 0.02 TP
WALL FORMULA
WALL AND WINDOW
ADDITIONAL ENERGY ΔE (MeV)
50
40
30
20
10
0
37.5
38.0
38.5
39.0
39.5
Z²/A

Figure 3.

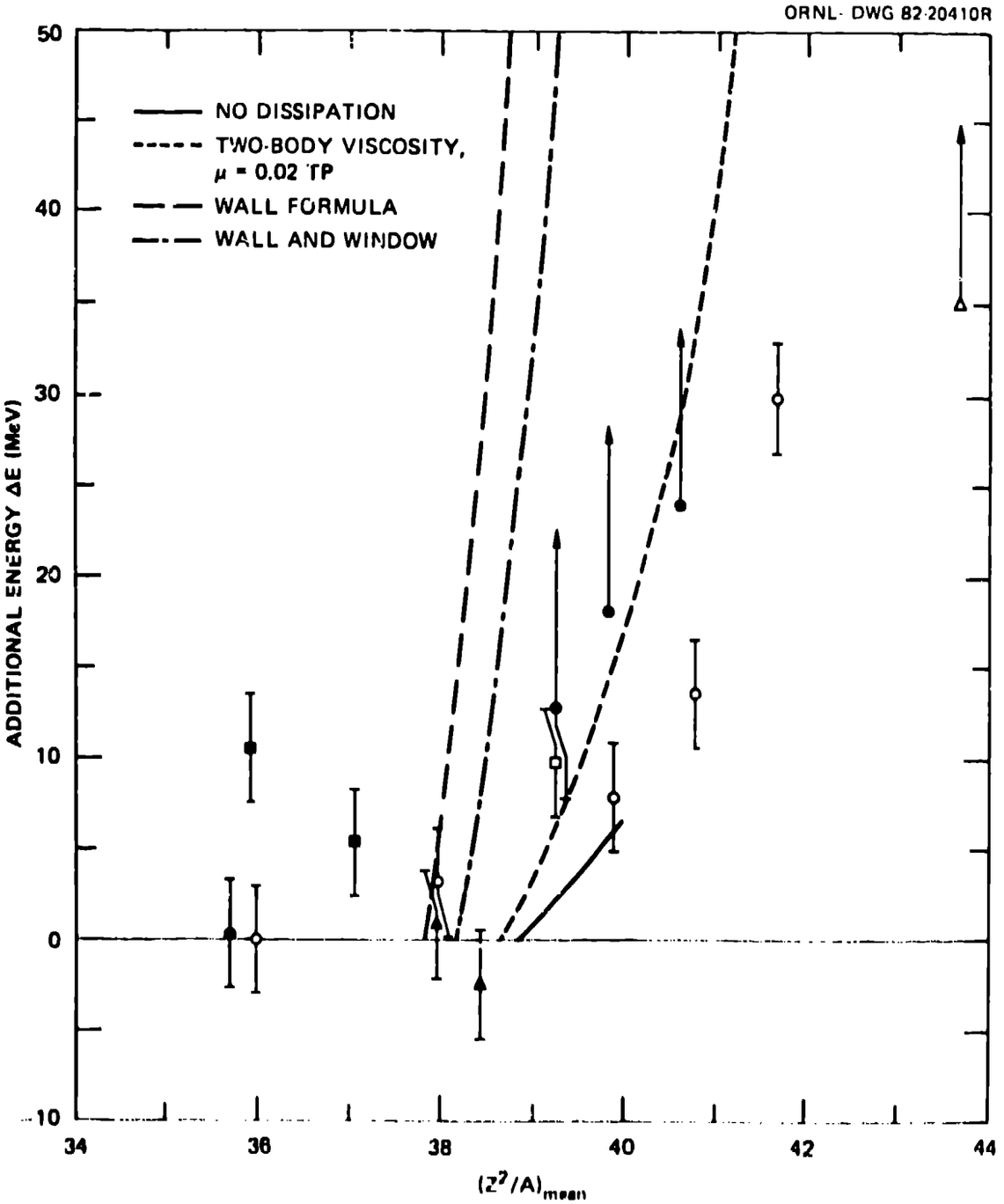
ORNL- DWG 82-20410R
NO DISSIPATION
TWO-BODY VISCOSITY, μ = 0.02 TP
WALL FORMULA
WALL AND WINDOW
ADDITIONAL ENERGY ΔE (MeV)
50
40
30
20
10
0
-10
34
36
38
40
42
44
(Z²/A)mean

Figure 4.